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Graphene-Based Ultra-Light Batteries for Aircraft

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The Team

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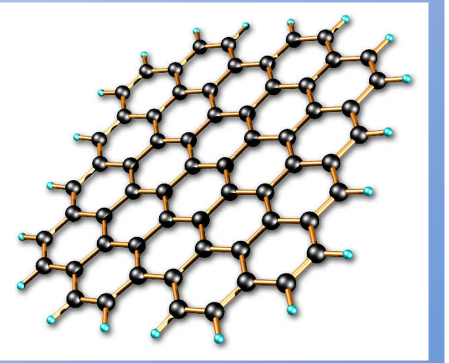
Outline

- The innovation
- Background
- Technical approach
- Impact of the innovation
- Results of the Seedling effort to date
- Distribution/Dissemination—getting the word out
- Next steps

The Innovation

- Develop a graphene-based ultracapacitor prototype that is flexible, thin, lightweight, durable, low cost, and safe and that will demonstrate the feasibility for use in aircraft
- These graphene-based devices store charge on graphene sheets and take advantage of the large accessible surface area of graphene (2,600 m^2/g) to increase the electrical energy that can be stored.



- The proposed devices should have the electrical storage capacity of thin-film-ion batteries but with much shorter charge/discharge cycle times as well as longer lives
- The proposed devices will be carbon-based and so will not have the same issues with flammability or toxicity as the standard lithium-based storage cells.

Impact of the Innovation

- Commercial ultracapacitors are currently being used in transportation. A fleet of buses near Shanghai has been running on ultracapacitors for the past several years. Only disadvantage: frequent stops due to low energy densities.
- Graphene-based ultracapacitors promise energy densities greater than existing commercial electrochemical ultracapacitors by an order of magnitude. They also have greater power densities than lithium-ion batteries by an order of magnitude.
- GO, the precursor for the production of graphene, is manufactured on the ton scale at low cost as opposed to lithium, which is a limited resource that must be mined throughout the world.
- A robust, lightweight, flexible, thin, and inexpensive energy storage device with energy and power densities superior to those of state-of-the-art energy storage devices will greatly benefit NASA and the nation's aeronautics.
- Such revolutionary energy storage devices will radically reduce the mass and weight of energy storage and supply devices resulting in more efficient aircraft.

What is Graphene?

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- **Graphene is a revolutionary new allotrope of carbon (a single atomic layer of graphite) with extraordinary properties:**
  - ***Surface area*: 2630 m^2/g**
  - ***Electrical conductivity*: 10^6 Ω^{-1}cm^{-1} (Cu: 0.6x10^6 Ω^{-1}cm^{-1})**

    π-electrons act like photons – mobility is determined by graphene quality
  - ***Thermal conductivity*: 5000 Wm^{-1}K^{-1} (Cu: 401 Wm^{-1}K^{-1})**
  - **Strongest material ever discovered: Tensile strength ~ 130 GPa (steel ~0.4 GPa)**
  - **"Graphene is complicated and expensive to make in large sheets" *Nature*, Nov. 20, 2013**

Background

There are two main established methods for the storage and delivery of electrical energy:

- Batteries
  - Store energy with electrochemical reactions
  - High energy densities
  - Slow charge/discharge cycles
  - Used in applications requiring large amounts of energy → aircraft

- Electrochemical capacitors
  - Store energy in electrochemical double layers
  - Fast charge/discharge cycles
  - Low energy densities
  - Used in electronics devices – Large capacitors are used in truck engine cranking

Current Aircraft Batteries

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- General Aviation and Light aircraft → Lead acid batteries
- Larger aircraft and helicopters→ Nickel cadmium batteries
- Aircraft manufacturers are beginning to use Lithium Ion batteries due to their larger capacitances per unit weight.
  - Li-ion batteries still have low power densities
  - Performance is mainly controlled by
    - diffusion of Li ions
    - electron conductivity in the electrolyte
  - Recent approaches to increase performance involve
    - Use of nano-structured electrodes for shorter ion diffusion distances
    - Introduction of dopants to increase ion transport efficiency
  - However, stable performance over thousands of charge/discharge cycles has not been achieved.

Expected Performance

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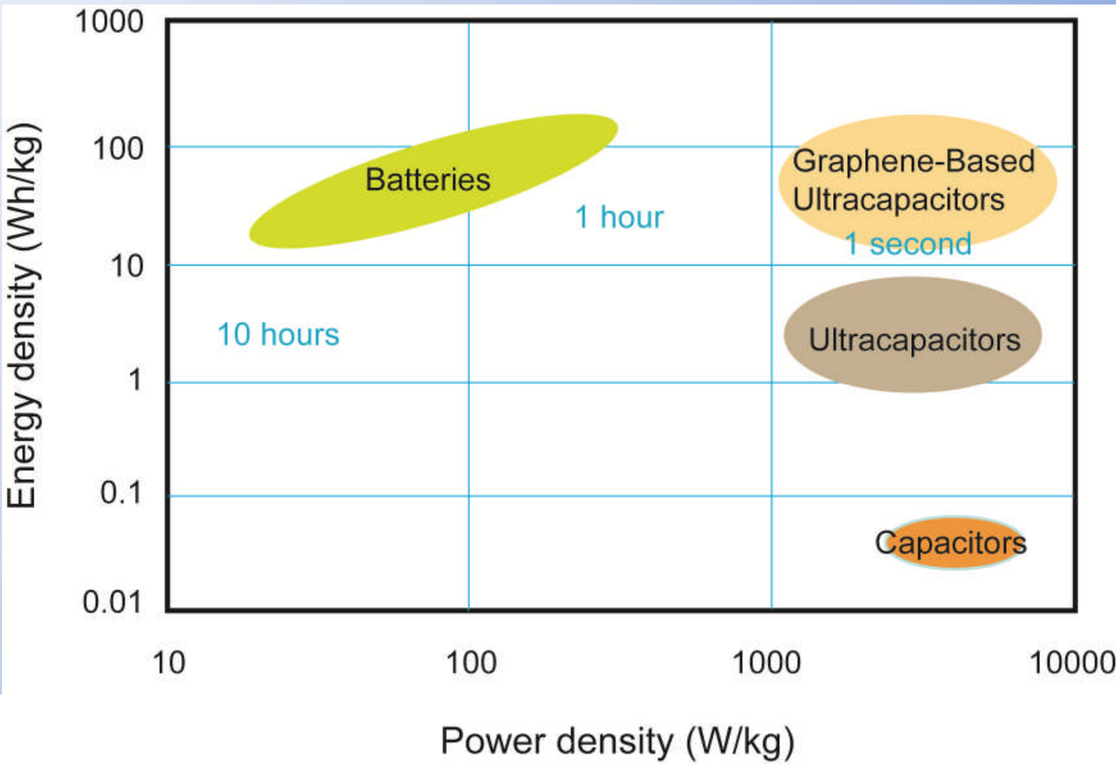
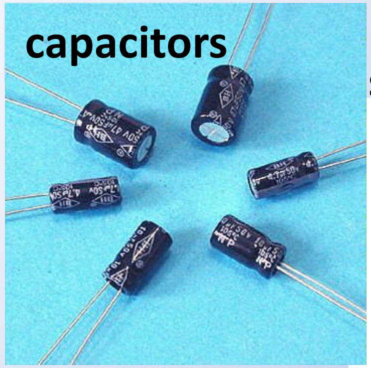
Our graphene-based ultracapacitors:

- High power densities of ultracapacitors
- High energy densities due to huge surface area of graphene

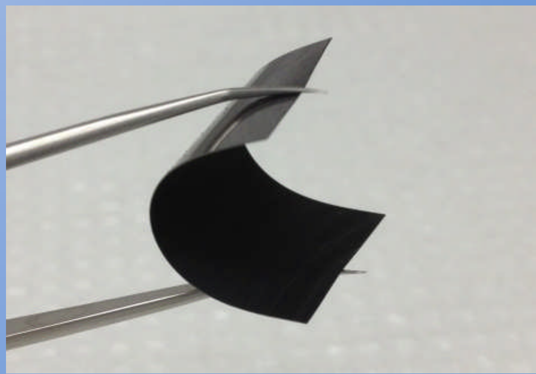




Energy and power density comparison for batteries, conventional ultracapacitors, and the expected performance of graphene-based ultracapacitors. Charging times are shown in blue.

Technical Approach

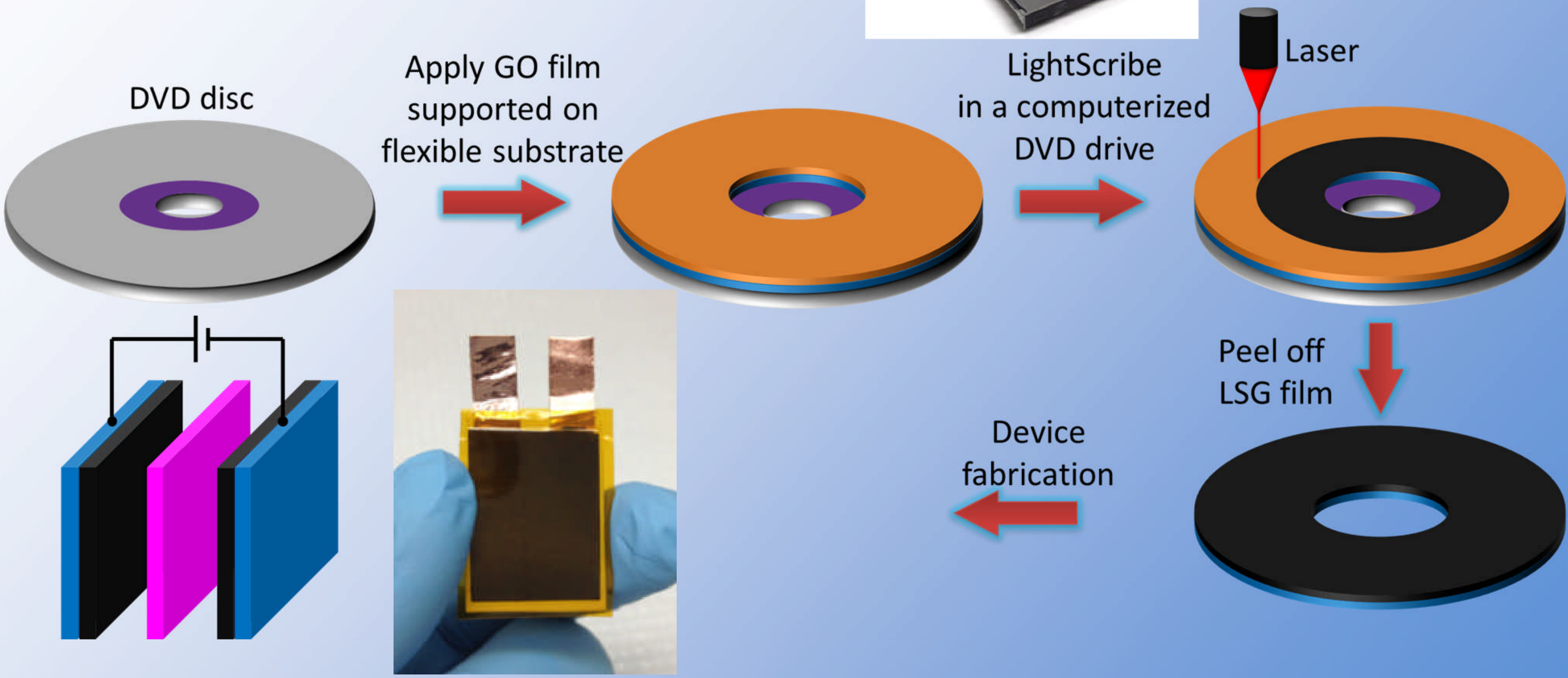
- Methods to reduce Graphene Oxide into graphene include chemical, thermal, and flash reduction
- UCLA Co-Investigator developed a light scribe lithography method that produces high quality graphene films that have high electrical conductivity and specific surface area, and can be used directly as electrodes in energy storage devices.*
- We are producing Laser Scribed graphene as well as direct laser reduced graphene.
- Ultracapacitors are assembled with graphene sheets using liquid electrolyte



*El-Kady, M.F., V. Strong, S. Dublin, and R.B. Kaner, *Science* 335 (2012) 1326-1330

UCLA Laser Scribe Method

Making graphene supercapacitors
is as easy as burning a DVD



M.F. El-Kady, V.Strong, S.Dubin, R.B. Kaner, *Science* 335, 1326-1330 (2012)

Results: XPS Analysis

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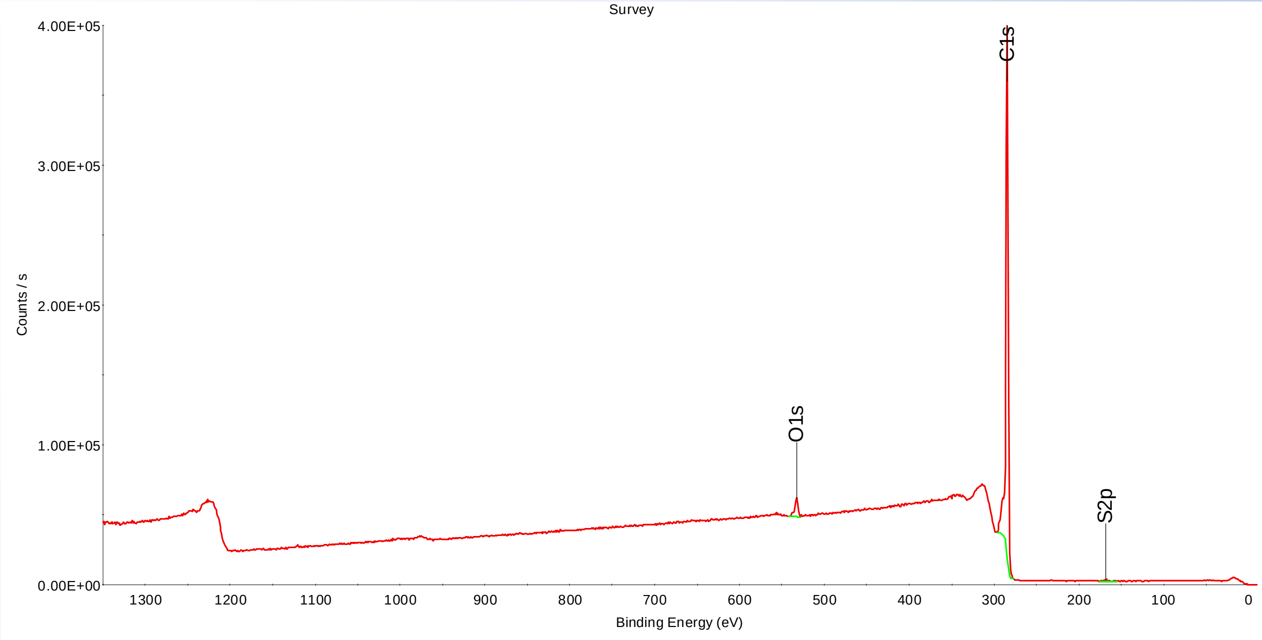

XPS survey scan of a representative graphene sample showing the relative presence of carbon (C1s peak) and oxygen (O1s peak).

- The carbon content of the graphene sheets ranges from 96% to 98.5% while the oxygen content is in the range of 1.4% to 3%.
- In comparison, more widely used chemical reduction methods reduce oxygen content to 10% or higher. Our laser reduction method produces a more pure graphene sample.
- The carbon and oxygen content of the unreduced graphene oxide ranges between 66% to 70% and 29% to 32% respectively.

Results: Raman Spectrum

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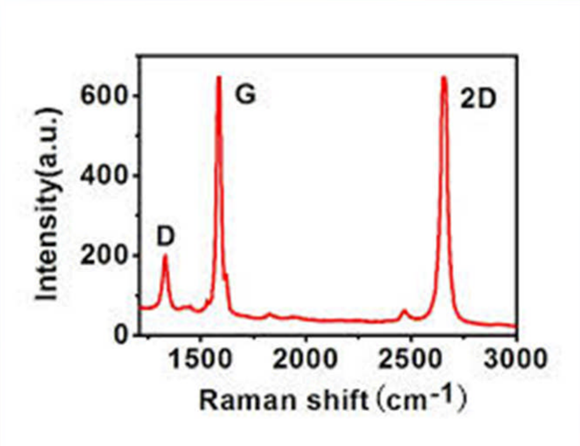
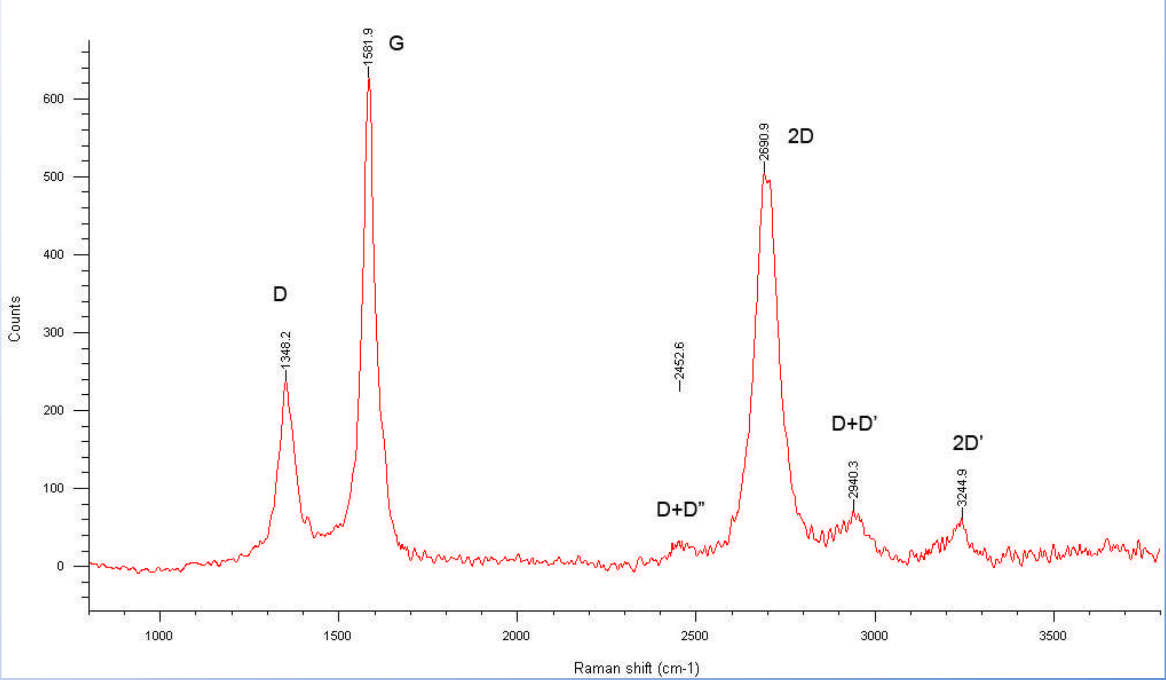


Ideal Raman spectrum of graphene.



Actual Raman spectrum of a graphene sheet.

- Raman spectrum of the graphene sheet shows the *G*, *2D*, *D+D”*, and *2D’* bands that are characteristic of graphene, as well as a Raman-forbidden band, *D+D’*, that arises from defects.
- Defects could be edges, functional groups, or structural disorders

Results: Ultracapacitor Performance

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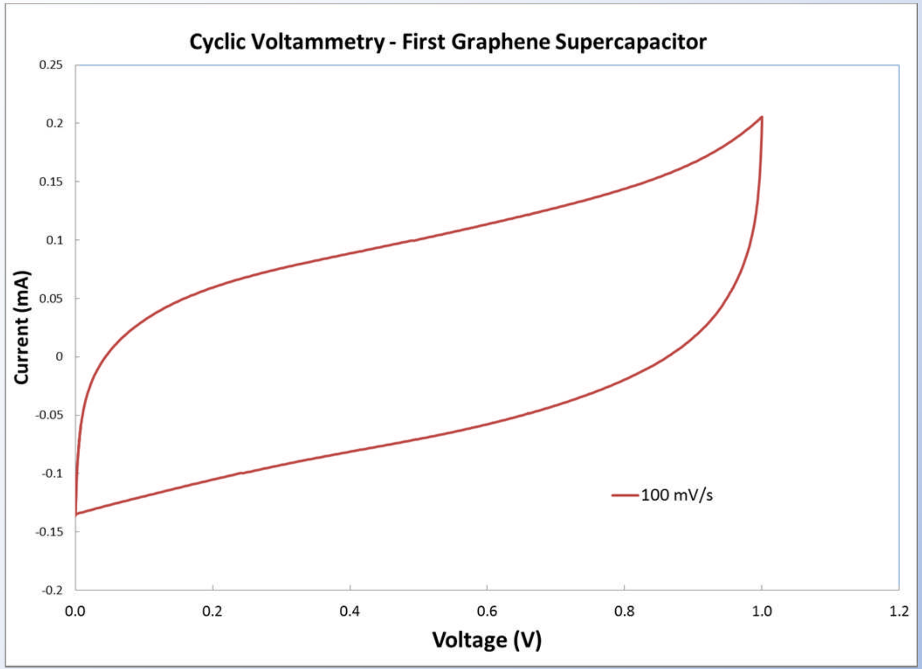

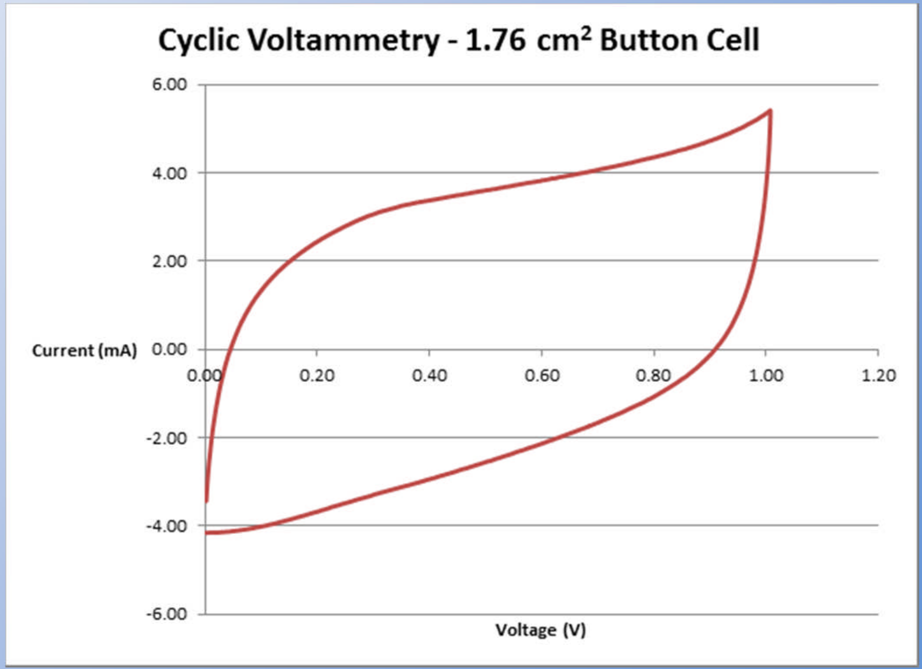

Cyclic voltammetry profile for first parallel-plate graphene capacitor prototype at 100 mV/s.

Cyclic voltammetry profile for parallel-plate graphene button cell capacitor prototype at 100 mV/s.

Ultracapacitor Performance

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Curve	dV/dt (V/s)	Capacitance (F)	Capacitance (F/cm^2)
1	1	1.38E-02	6.00E-03
2	0.1	2.45E-02	1.07E-02
3	0.01	5.50E-02	2.39E-02

- Capacitance and capacitance per unit area values were obtained from cyclic voltammetry at different scan rates for the button cell prototype.
- Capacitance per unit area increased from 2.4 mF/cm^2 for the early pouch cell to 24 mF/cm^2
- Results are very encouraging and show that we should be able to increase the capacitance as we scale up the devices.

Ultracapacitor Performance

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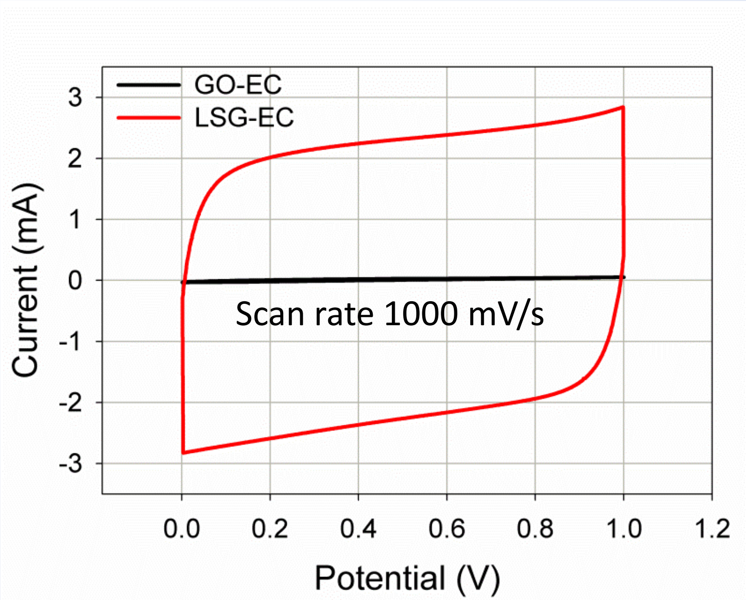
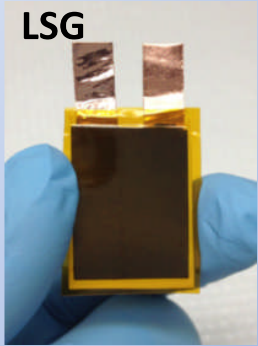
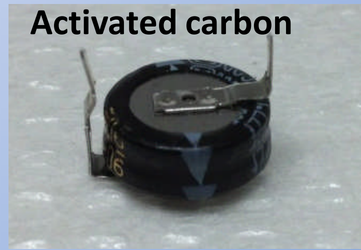
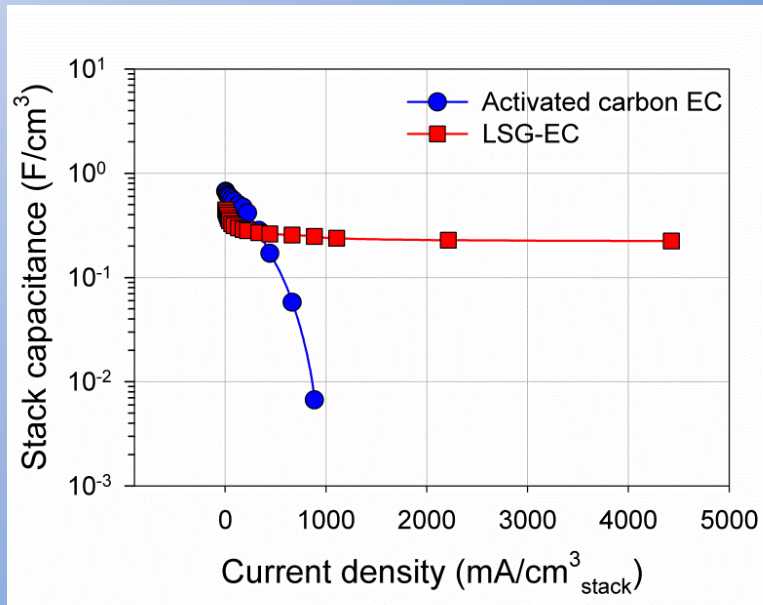
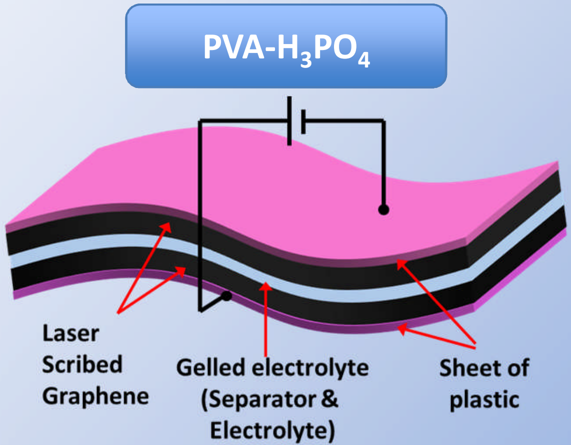


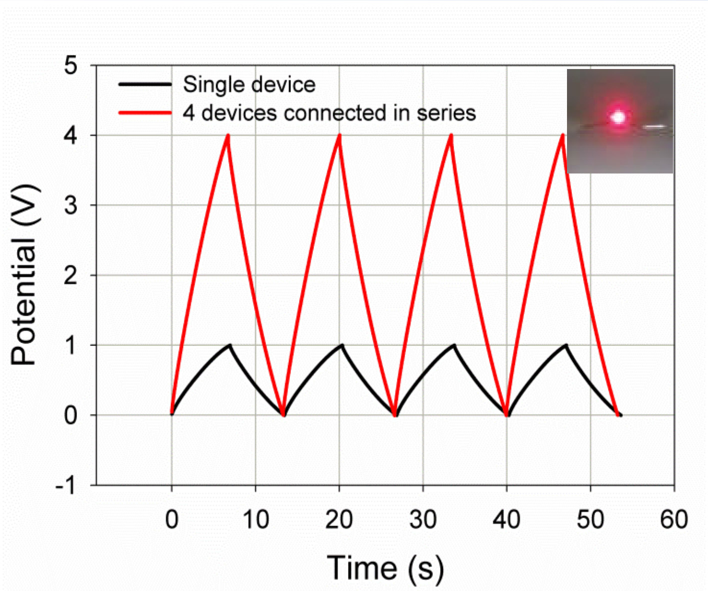


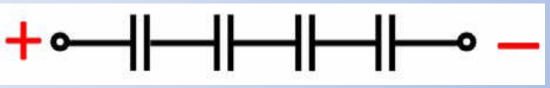


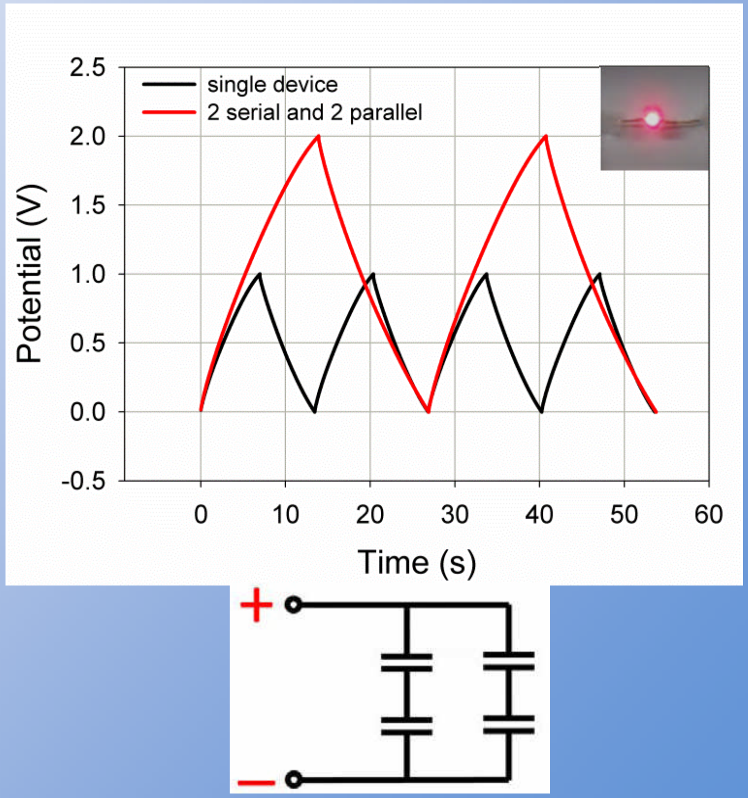




Tandem Supercapacitors







Cycling and Shelf-Life

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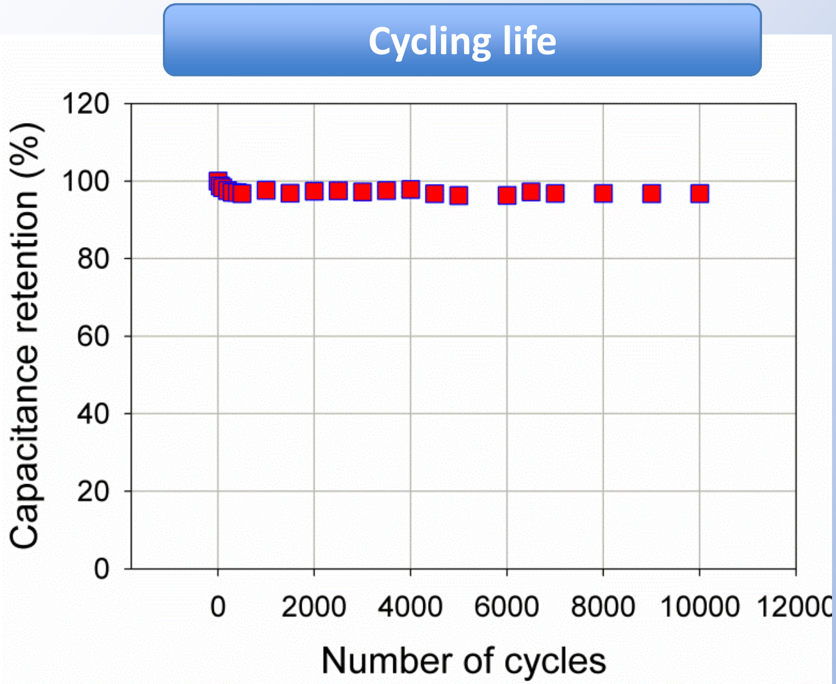
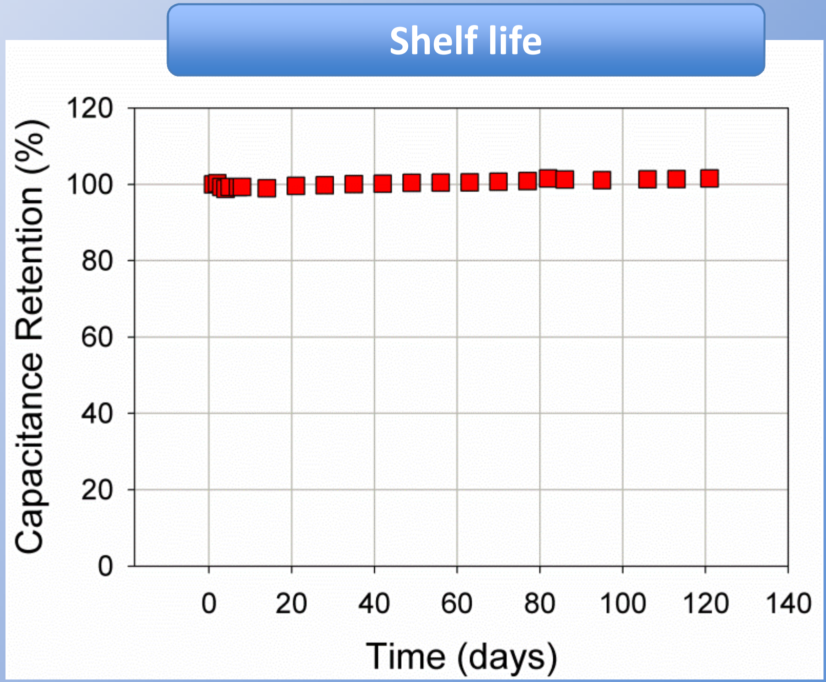
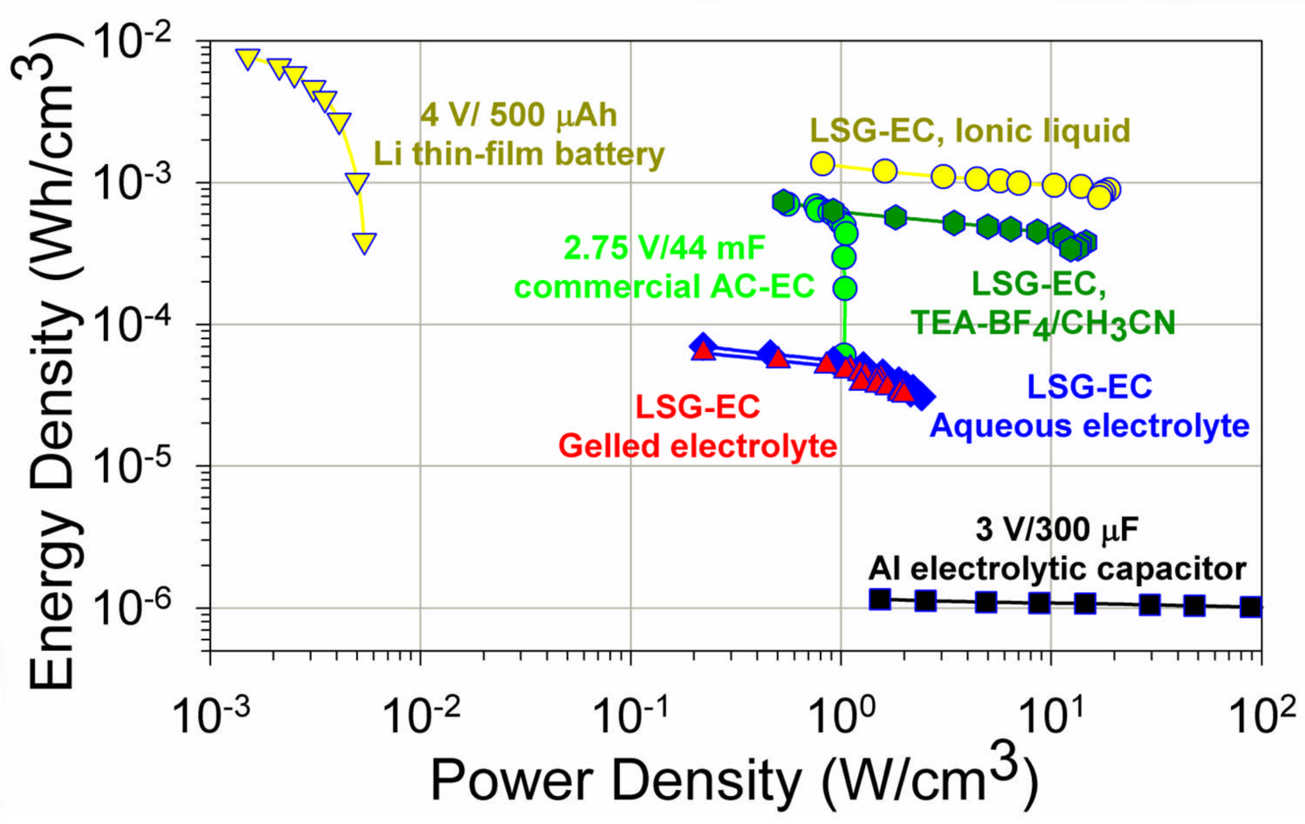




LSG vs. Commercial Supercapacitors

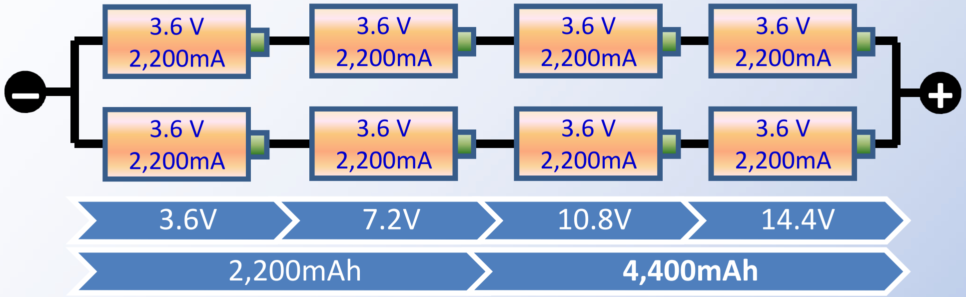


- The plot shows the energy density and power density of the stack for all the devices tested (including current collector, active material, electrolyte and separator).
- Additional features: flexible, lightweight, current collector free and binder free

Distribution/Dissemination

- Graphene-based unltracapacitors for aeronautics applications
  - Invited paper to be presented at the 247th ACS National Meeting, Dallas, TX, March 16-20, 2014

Next Steps



- Increase in voltage produces a substantial increase in the energy density of a supercapacitor ($E = \frac{1}{2}CV^2$)
- Investigate new solvents and electrolytes with higher ion conductivity that would yield voltages suitable for aeronautics applications
- Investigate combinations of these electrolytes for higher performance
- Scale up graphene sheet production with our laser system
- Build prototypes to demonstrate feasibility of graphene-based ultracapacitors for aeronautics applications